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S. S. Olivier, L. Seppala, K. Gilmore, L. Hale, W. Whistler

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LSST Camera Optics

Scot S. Olivier¹, Lynn Seppala¹, Kirk Gilmore², Layton Hale¹, Wayne Whistler¹, and the LSST camera team.

1. Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550

2. Stanford Linear Accelerator Center, P.O. Box 20450, Stanford, CA 94309

ABSTRACT

The Large Synoptic Survey Telescope (LSST) is a unique, three-mirror, modified Paul-Baker design with an 8.4m primary, a 3.4m secondary, and a 5.0m tertiary feeding a camera system that includes corrector optics to produce a 3.5 degree field of view with excellent image quality (<0.3 arcsecond 80% encircled diffracted energy) over the entire field from blue to near infra-red wavelengths. We describe the design of the LSST camera optics, consisting of three refractive lenses with diameters of 1.6m, 1.0m and 0.7m, along with a set of interchangeable, broad-band, interference filters with diameters of 0.75m. We also describe current plans for fabricating, coating, mounting and testing these lenses and filters.

1. INTRODUCTION

1.1. The Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST) [1, 2] aims to perform the most comprehensive astronomical survey in history by imaging $\sim 20,000$ square degrees of the sky in 6 colors ($0.33 - 1.0 \mu\text{m}$) down to a magnitude of ~ 26.5 (AB) in a 10-year campaign of 15 second exposures using a ~ 3.2 gigapixel digital camera with a field of view of ~ 10 square degrees. This survey will catalog ~ 3 billion galaxies and discover ~ 2.5 million Type Ia supernovae. It will discover $\sim 10,000$ primordial Solar System objects in the Kuiper Belt and catalog 90% of the near earth asteroids larger than ~ 300 meters in diameter. Specific measurements will include the spatial correlations of weak gravitational lensing of background galaxies, and the spatial distribution of clusters of galaxies. Combined with studies of supernovae detected by LSST, these measurements will determine fundamental cosmological parameters and constrain the nature of the mysterious “dark energy” and “dark matter”.

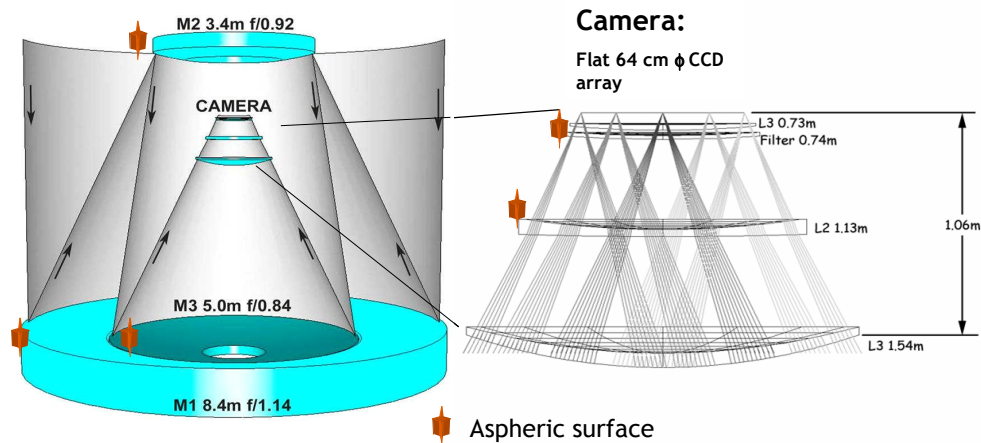


Figure 1. LSST optical design includes 3 large mirrors, 3 large lenses and a set of 6 large transmission filters.

1.2. LSST Optical Design

The baseline optical design for the LSST is a modified Paul-Baker 3-mirror telescope that includes a 5m tertiary mirror (M3) coplanar with an 8.4m primary mirror (M1). After a first reflection on M1, the optical beam converges on the

3.4m convex secondary mirror M2. From M2, the reflected beam diverges toward M3, and is then focused toward a 3-element correcting camera located in front of M2 on the optical axis (Figure 1). The current design employs three aspheric mirrors, and two of the refractive elements in the camera have aspheric surfaces. The three-mirror telescope system delivers, without the camera corrector optics, a spherical wavefront on axis that will greatly help in initial assembly and alignment. The optical prescription is given in Table 1.

Table 1. LSST baseline optical prescription for r band filter: all units are mm except as noted.

Surface	Radius of curvature	Center thickness	Outer optical clear aperture semi-diameter	Inner optical clear aperture semi-diameter	Name	Aspheric departure from best-fit parabola (BFP) or over annulus
1		1345.5				
2		4810.7	4327	2412		
3	-19835	-6156.2	4180	2558	Primary	0.111
4	-6788	6390	1700	900	Secondary	0.017
5	-8344.5	-3631.261	2508	527	Tertiary	0.403
6	-2824	-82.230	775		L1	
7	-5021	-412.642	775		L1	
8		0				
9	-	-30	509		L2	
10	-2529	-357.5	509		L2	
11		0				
12	-5624	-17.7	380		Filter	
13	-5597	-43.3	380		Filter	
14		0				
15	-3169	-60	352		L3	
16	13360	-28.5	352		L3	
Image			317		Focal Plane	
Surface	Conic Constant	y^4	y^6	y^8	y^{10}	
Primary	-1.215		1.381E-24			
Secondary	-0.222		-1.274E-20	-9.68E-28		
Tertiary	0.155		-4.50E-22	-8.15E-30		
L2	-1.57		1.656E-18			
L3	-0.962					

This optical design delivers a flat focal plane with a 3.5-degree diameter field of view (FOV) and a diffraction image spot size about 0.2 arcsec FWHM for 5 spectral bands covering a wide wavelength bandpass (from 400 to 1030nm). In addition, the LSST is a very fast telescope (f/1.234) with a plate scale of 50microns/arcsec and a detector diameter of 0.64m. The 10-micron pixel size detectors match the superb performance in image quality.

The combination of large diameter optics with fast f/# and a large detector at the focal plane makes the LSST a unique facility achieving an etendue (defined as the product of telescope collecting area and field of view) of $318 \text{ m}^2\text{deg}^2$, a factor of >50 beyond current existing facilities. This etendue value takes into account the large central obscuration of 5.1m in diameter and the variable vignetting toward the edge of the field (11.2% at the edge).

The wide range of wavelengths specified for the LSST requires some adjustments for operating at different spectral bands in order to preserve the high image quality. First, filters with different passbands need to be inserted to change the spectral range. Each filter has a unique central thickness to compensate for chromatic difference in aberrations. Thicknesses range from 26.3 mm in the U band to 13.5 mm in the Y band. Furthermore, some filters have a slightly different second radius of curvature to further correct for chromatic aberration. The central i-band filter, the y-band filter and the z-band filter are equi-meniscus, with radii of curvature of 5624 mm convex and concave. The second concave radius of other filters varies from 5507 mm in the u band, 5564 in the g-band and to 5597 in the r band. Second, the entire camera assembly is axially refocused, ranging from 3.505 mm away from the tertiary in the u band to 0.5843 mm toward the tertiary in the Y band. The negative lens L2 is kept at a fixed position for all wavelengths.

1.3. LSST Camera

The LSST camera is a wide-field optical ($0.33\text{--}1\ \mu\text{m}$) imager designed to provide a 3.5° field of view with better than 0.2 arc second sampling. The image surface is flat with a diameter of approximately 64 cm. The detector format will comprise a mosaic of 16 Mega-pixel silicon detectors providing a total of approximately 3.2 Giga-pixels. The camera includes a filter changing mechanism and shutter. It is positioned in the middle of the telescope where cross-section area is constrained by optical vignetting, and heat dissipation must be controlled to limit thermal gradients in the optical beam. The camera must produce data of extremely high quality with minimal downtime and maintenance. A schematic cross section of the camera assembly is shown in Figure 2.

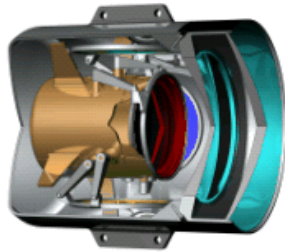


Figure 2. Cross-section of LSST camera design.

2. CAMERA OPTICS

The LSST camera optics consist of 3 fused silica lenses with diameters of 1.6 m, 1.1 m and 0.73 m that correct for field aberrations, along with interchangeable filters with diameters of 0.78 m that give spectral coverage from the UV to near IR. The three lenses along with 0.64 m diameter detector array are housed in a canister, ~ 1.6 m in diameter, the size of the largest lens, as shown in Figure 3.

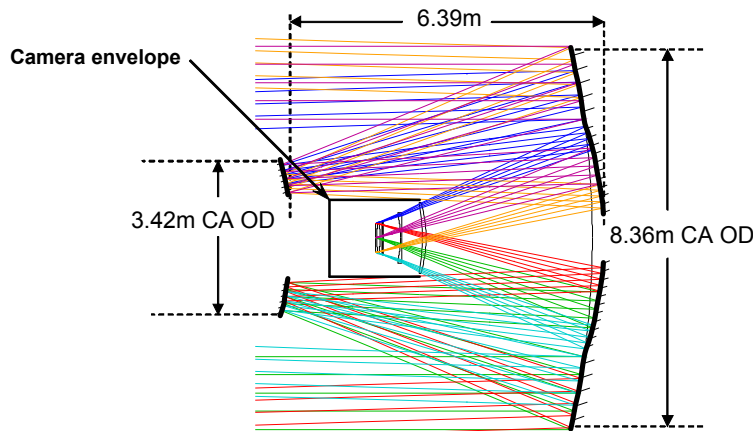


Figure 3. Optical schematic of LSST showing envelope for camera assembly.

The necessity for the refractive optics in the camera comes from two sources. First, L3 is required as a window and vacuum barrier for the dewar containing the detector array. Second, the filters are required for science. L1 and L2 are then required to minimize chromatic effect of L3 and filters. Integrated design of mirrors and lenses improves design. For example, adding asphericity to L2 simplifies testing and helps to reduce asphericity on secondary mirror

A schematic of the LSST camera optics, including the rays bounding the light distribution incident on the central and peripheral field points, is shown in Figure 4. The largest lens, L1, is nominally 1.6 m in diameter. The current design of L1 calls for an edge thickness of ~ 3.3 cm and a center thickness of ~ 6.7 cm. The middle sized lens, L2, has a central thickness of 3.0 cm. The space between L2 and the filters is 36 cm, which provides adequate space to accommodate the filter interchange. The smallest lens, L3, is also the vacuum barrier for the cryostat containing the detector array. There

is 2.85 cm between the inner surface of L3 and the focal plane. The central thickness is specified in order to provide a significant safety margin for potential fracture of L3 due to the pressure differential. Empirical data shows that a thickness ratio of ~ 12 is adequate to provide this safety margin, which yields a thickness of 6.0 cm for the 73 cm diameter lens. The filters consist of multi-layer dielectric interference coatings deposited on fused silica substrates. The baseline design has the first surface of the filters concentric about the chief ray in order to keep the angles of the light rays passing through the filters as uniform as possible over the entire range of field positions. The central thickness and the curvature of the second surface are optimized for image quality. The minimum center thickness is 1.35 cm. Detailed parameters for the camera optics are given in Table 1.

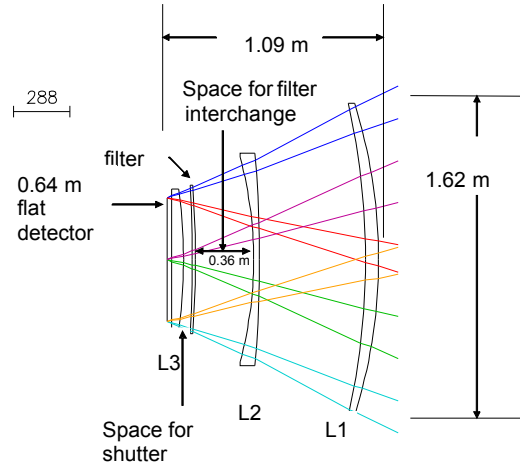


Figure 4. Camera optics schematic.

2.1. Camera Optics design considerations

The following issues have been considered in the design of the LSST camera optics.

1. What type(s) of glass are needed for the camera optics?
2. Can the required glass be obtained?
3. Can these large, thin, transmissive optics be fabricated?
 - L1 will be one of the largest lenses ever made
4. How will the optics be mounted?
5. How will we know if the optics, as fabricated, meet the required performance specifications?
6. What coatings are required for the optics, especially the filters?
7. Can the required coatings be fabricated?
8. What is the plan for future work on camera optics?

These issues are addressed in the subsequent sections.

2.2. Camera optics glass

The current camera optics design can meet all design requirements using fused silica substrates. We have identified a qualified vendor, Corning, for the required fused silica glass. The Corning manufacturing process for fused silica can produce glass of the required size and quality. Corning estimates of cost and schedule to produce the required fused silica glass have been used as input for LSST camera optics schedule and budget.

2.3. Camera optics fabrication

The main challenge in the production of the LSST camera optics is the fabrication of large, thin lenses and filter substrates. In order to assess this risk, a team of LSST representatives has visited multiple commercial vendors, supplied these vendors with documentation on the baseline optics designs as described above, and initiated discussions with the vendors concerning the specifications, cost, schedule and technical risk of fabricating these optics. The preliminary feedback from all vendors indicates that commercial costs and schedules are consistent with LSST budgetary and

program planning estimates. Furthermore, the responses from multiple commercial vendors demonstrate that a substantial industrial base exists for fabricating large, thin optics.

2.4. Camera optics mounts

The optic mounts provide the interface between L1, L2, L3 and filter optics and the structures that support them. These interfaces may include adjustment capability for alignment purposes. In some cases, the vendors may be asked to supply the optics already installed and qualified in the mounts.

2.4.1. Requirements and constraints

1. L1 and L3 mounts must be gas tight. L1 contains dry nitrogen within the camera housing and L3 is the vacuum window for the cryostat containing the focal plane.
2. All optics must operate over a fairly wide temperature range of order 30° C. For steel mounts and fused silica optics, the differential radial expansion would be 254 μm for L1, 182 μm for L2, 117 μm for L3 and 126 μm for the filters. The values would be 1.6 times greater for stainless steel mounts and 2.2 times greater for aluminum mounts.
3. Alignment tolerances must be maintained for changing conditions at the telescope, including orientation, temperature and barometric pressure.
4. As a precaution, the optic should be demountable such as to allow refurbishment.

2.4.2. L1-L2 subassembly

In terms of optical correction, L1 and L2 are the most significant optics in the camera. Their alignment to one another is therefore more critical, and the pair forms logical datums to use in aligning the focal plane array, L3 and the filter. In addition, the size and location of L1 and L2 on the front end of the camera (away from the shutter and filter changer) make an aligned and tested subassembly a reasonable package for an optics vendor to produce. A repeatable kinematic interface allows the front-end assembly (L1 and L2) to be easily removed from and reinstalled on the camera housing to provide ample access to components inside such as the filter carousel.

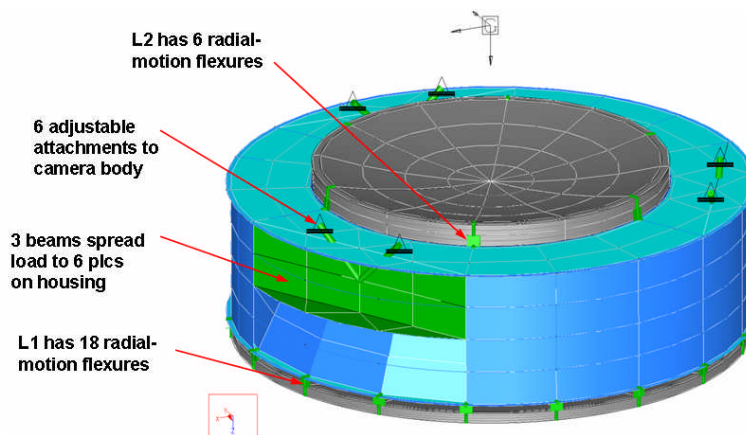


Figure 5. Finite element model of the L1-L2 subassembly, featuring a common structural cell and radial-motion flexures between the optics and the cell.

The finite element model shown in Figure 5 confirmed the feasibility of creating an independently stiff cell mount on which to attach both L1 and L2 optics. Between the cell mount and L1 and L2 are, respectively, 18 and 6 radial-motion flexures, which allow for differential thermal expansion. These numbers of supports limit gravity-induced edge ripple to less than 1 μm P-V. It is expected that each optic will be measured in the mount during fabrication and that repeated polishing-measurement steps will require simple and repeatable remounting. To accomplish this, the flexure mounts will be made with detachable pads that permanently stay with the optic once bonded. Between each pad and flexure, there will be a spherical joint preloaded together with a pair of springs. The joint is easily separated for disassembly and

typically repeatable to less than 1 μm . In addition, it provides angular degrees of freedom. The gas seal required for L1 will be made on the outer convex surface with a highly compliant seal, such as a tubular o-ring or u-cup, in a captive ring.

2.4.3. Filter bezel

The filter substrates differ from one another in their central thickness, ranging from 13.5 to 26 mm. The convex spherical radius is the same for all filters and is placed the same inside the camera, thus it is a logical surface for the bezel to register. The bezel can accommodate different filter thicknesses using shims, for example, to space off the clamp ring. Outwardly to the filter changer, all bezels are the same except for a means to encode the identification of each. A simple method for mounting optics is between two o-rings, one on the bezel and the other on the clamp ring. The compliance of the o-rings accommodates tolerance in the parts and differential thermal expansion. Large-diameter o-rings are normally made from extruded stock so the cross section is well controlled. Further there is no need to join the ends since this mount does not have to form a seal.

2.4.4. L3 as a vacuum window

The array of detectors at the focal plane must operate at a constant temperature near 170 K. To eliminate natural convection heat transfer, the focal plane array will be housed in a vacuum cryostat using L3 as the vacuum window. Supporting the focal plane array on flexures and using multi-layer insulation inside the cryostat will minimize conduction and radiation heat transfer. Unavoidably, radiation heat transfer from L3 is the dominant external heat load on the focal plane array, estimated to be of order 140 W.

Mechanical stress in the vacuum window has been considered in the optical design by making L3 thick enough to safely carry the atmospheric pressure load at sea level. Although not planned, it is possible to achieve even greater safety factor by applying radial edge pressure, which both reduces the bending moment for a curved optic and sets up compressive stress that counters tensile stress due to bending. Experience with large lenses as vacuum windows comes from ICF laser systems such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). These systems have the added complication that the lenses become damaged with use, yet they can be operated safely for many years by monitoring damage sites in lenses with diagnostics. While no damage is expected for LSST, the focal plane array near L3 has high enough resolution to detect cracks of any consequence.

A safe design may be determine using Equation 1 to find the allowable tensile stress that will propagate just one crack, thus avoiding implosion by a controlled leak down [3]. It depends on the diameter of the optic at the support and a material factor determined from destructive tests, fused silica in this case. For L3, the result is 4.53 MPa (657 psi). For a crack to propagate, however, there first must be a flaw whose size may be determined using Equation 2, the Griffith fracture criteria. The result for fused silica is 8.7 mm diameter, assuming a half-penny crack that penetrates the surface. For an optic without flaws, this design stress has a safety factor in excess of 10:1.

A finite element model of L3 on a realistic support was developed to determine the stress under load. As Figure 6 shows, atmospheric pressure at sea level does not exceed the design stress. Lower pressure at the telescope site, of order 70%, will provide even greater design margin.

$$\sigma_t = \frac{K_f}{\sqrt{d}} \quad K_f = 3.79 \text{ MPa} \cdot \text{m}^{1/2} \quad (1)$$

$$a = \frac{1}{\pi} \left(\frac{K_{1c}}{\sigma_t} \right)^2 \quad K_{1c} = 0.748 \text{ MPa} \cdot \text{m}^{1/2} \quad (2)$$

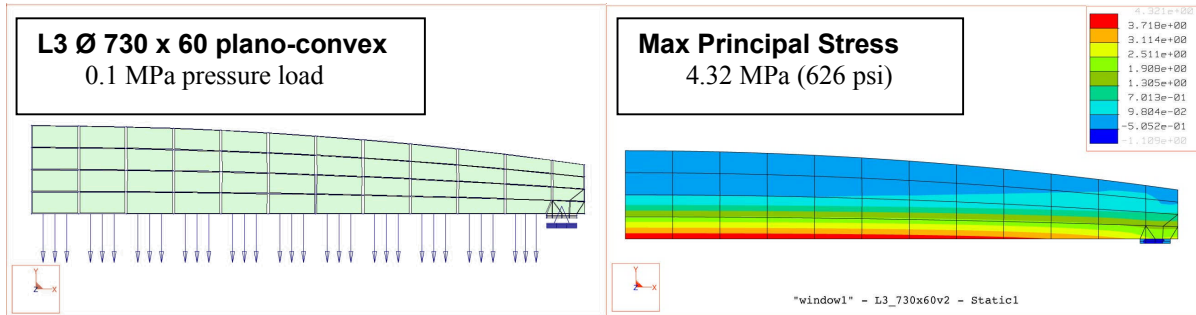


Figure 6. Finite element model (left) and plot of maximum principal stress (right). Positive stress is tensile in the normal sign convention used here. The plot looks unsymmetrical because the upper compressive stress shows up in a plot of minimum principal stress, which is the mirror image of this one.

2.4.5. L3 vacuum mount

A thin elastomer gasket between the optic and the housing carries the vacuum load while an o-ring in the clamp ring maintains preload when the cryostat is vented. The thickness-to-width ratio of the gasket has a strong effect of the degree of compression under approximately 26 kN (5900 lb) of vacuum load. 7 shows a finite element analysis using a Viton gasket 3 mm thick by 20 mm wide, and the predicted compression is only 14 μm . Friction at the gasket keeps the optic centered. There will be an o-ring seal between the housing and clamp ring so that the gasket is not the primary seal. The cavity outside the gasket may be separately evacuated to provide a double seal.

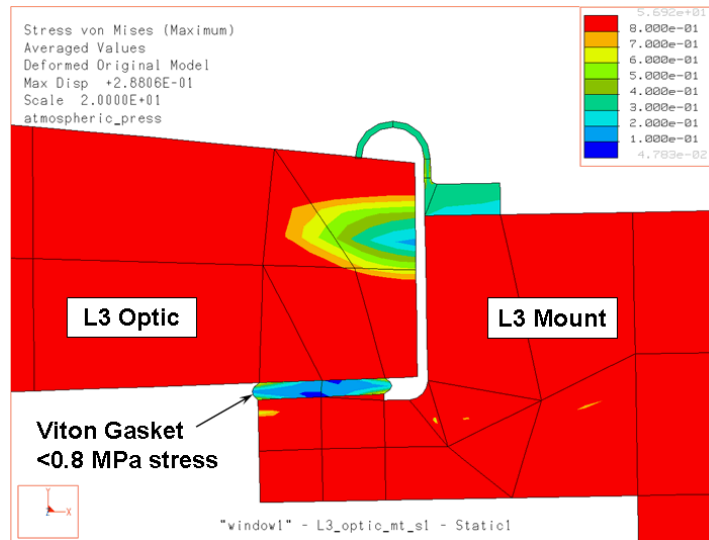


Figure 7. Plot of von Mises stress due to atmospheric pressure on the L3 optic and mount. The deflected shape is exaggerated 20x to show compression of the gasket, which is minor compared to deformations of the optic and mount.

2.5. Null testing

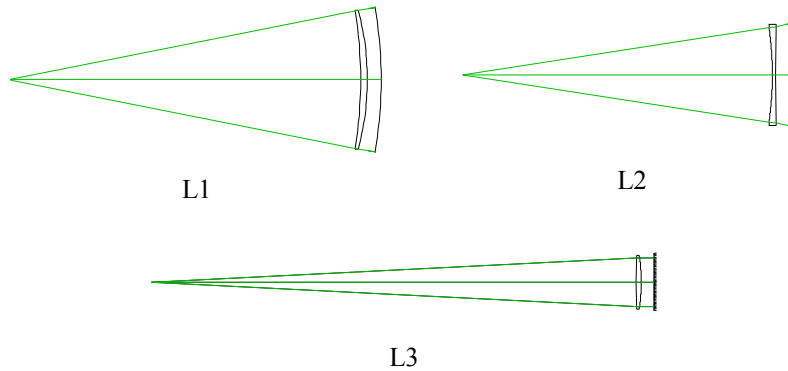


Figure 8. Schematic of null tests using spherical mirrors for L1 and L2 and a plano mirror for L3.

A key aspect of the corrective camera optics that enables fabrication using industry standard techniques is that they have relatively simple null tests that are designed simultaneously with the full LSST. An eleven-configuration telescope design file incorporates these three null tests along with configurations for each of the six passbands and two additional alignment null tests. Schematic configurations of the lens null tests, using spherical mirrors for L1 (radius ~ 5.0 m) and L2 (radius ~ 3.1 m) and a plano mirror for L3, are shown in Figure 8. All null tests use a retroreflecting mirror to test the lens in double pass transmission. A perfect point source to the left of the lens is reimaged onto itself with a wavefront error less than $1/20$ wave at 633 nm. The null test design influences the final optics prescription. L1 is a spherical lens. Adding an asphere to L2 simplifies testing and helps to reduce asphericity on the secondary mirror. Adding a weak asphere on L3 provides an easy test for L3. Null tests are performed with optics mounted in the same manner as during operation in the camera. These null tests also serve as the quality assurance that the optics meet their specifications as fabricated. Tight control, on the order of 0.1%, on the fabricated focal lengths of these lenses is required to maintain a sufficiently flat focal plane.

2.6. Coatings

Once the lenses and filter substrates are fabricated, they must be coated. For the lenses, the coating is a relatively straightforward broad-band anti-reflection coating to minimize the optical loss through the system and the brightness of ghost images. The main challenge here is the size of the largest lenses. In the case of the filters, the coating is a relatively sophisticated multi-layer interference coating that is designed to transmit only light with wavelengths in a specified band, and to reject light at other wavelengths with a specified fidelity. The main challenge here is to deposit uniform coatings with the desired characteristics on the large, curved substrates.

In order to assess industrial capabilities for supplying the coatings required for the LSST optics, LSST project representatives have visited and/or initiated discussions with several commercial vendors. The preliminary feedback from vendors indicates that there are no unsolvable technical challenges, and at least two U.S. vendors have previously coated optics of similar size with similarly complex coatings. Other vendors are also interested in extending their current capabilities to enable coating of optics of the required sizes.

2.6.1. Filter characteristics

The current LSST filter complement (u,g,r,i,z,Y) is modeled after the Sloan digital Sky Survey (SDSS) system because it has demonstrated success in a wide variety of applications such as photometric redshifts of galaxies, separation of stellar populations, and photometric selection of quasars.

The extension of the SDSS system to longer wavelengths (Y-band) is mandated by the increased effective redshift range achievable with the LSST due to deeper imaging. The optimal wavelength range for the Y-band is still under investigation. The addition of a u-band will improve the robustness of photometric redshifts of galaxies, stellar population separation, and quasar color selection, and will provide significant additional sensitivity to star formation histories of detected galaxies.

The current LSST baseline design has a goal of 1% relative photometry and, as such, defines the general features of the filter set. The filter set wavelength design parameters are shown below, and the approximate FWHM transmission points for each filter are shown in Table 2.

- g – aligned with the Balmer break @400nm
- r – matches SDSS
- i – red side short of sky emission @826
- z – red side stop before H2O bands-starts ~930nm
- Y – red cutoff before detector cutoff

Table 2. Baseline LSST filter band-pass FWHM points in nm

Filter	λ_1	λ_2
U	330	400
G	402	552
R	552	691
I	691	818
Z	818	922
Y	970	1060

2.6.2. Filter design considerations

1. Beam that is incident on the filter has a focal ratio of f/1.234 with a 61.5% obscuration.
2. The filter is concentric about the chief ray so that all portions of the filter see the same angle of incidence range, about 14.2° to 23.6°.
3. No gaps should exist between filter band-passes, except in the spectral region between 930-960 nm where it is desirable to exclude variable water vapor absorption features.
4. Filter band-passes should not overlap.
5. Band-pass throughput should be as high possible.
6. The transition between stop and pass band should be less than 5% of the filter band-pass.

2.6.3. Filter models

The LSST filter set was modeled using the total system throughput including atmospheric extinction, mirror reflectivities, lens transmissivities, and detector quantum efficiency. The Palomar atmospheric extinction tables were used and scaled to Cerro Pachon using an airmass of 1.2. The resultant extinction in magnitudes was then converted to flux. The mirror data used for these calculations was “aged” aluminum where the deposition was ~ one month prior to mirror reflectivity measurements. The detector quantum efficiency curve used is detailed in a separate paper on the LSST detectors [4]. Figure 9 shows the ideal filter set and the models for atmospheric extinction, mirror and lens losses and the detector quantum efficiency superimposed on the ideal filter set. Factoring in the effects yields the results shown in Figure 10.

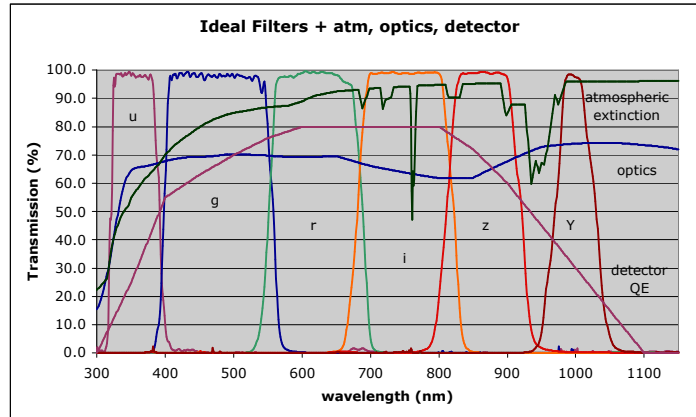


Figure 9. Ideal LSST filter characteristics and transmission curves for the atmosphere, optics, and detector.

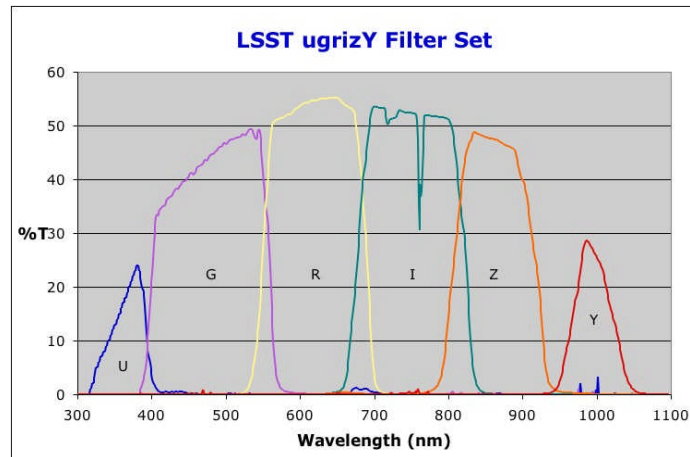


Figure 10. LSST filter characteristics including effects of the atmosphere, optics, and detector.

2.7. Future Work

Based on the initial assessment of commercial vendor capabilities, the following project execution plan has been developed for production of LSST camera optics.

- R&D Phase
 - Finalize optics design
 - Finalize coating specifications
 - Finalize optics mount design
- Construction Phase
 - Fabricate & test optics mounts
 - Fabricate & test lenses and filter substrates
 - Coat lenses and filters
 - Perform acceptance tests

In addition to these steps, we are also considering issuing an RFQ for the complete camera opto-mechanical assembly. This idea is based on feedback from multiple commercial vendors indicating interest in bidding on the complete assembly. A related consideration would be to issue contracts for opto-mechanical engineering studies to commercial vendors.

2.7.1. L3 vacuum window risk-reduction activities

The consequence of L3 failing catastrophically is so great that the safety margin should be verified through full-scale testing. This would occur in several stages beginning first with a mock optic in aluminum. This allows verification of the finite element model for both stress and deflection. Compression of the gasket would also be measured and if necessary design modifications would be made. The second stage tests would use flat optical glass with similar properties as the fused silica optic. The glass would be loaded beyond the design stress, perhaps two times, to establish a reasonable proof test for the real optic. Then the tensile surface would be intentionally damaged to simulate a flaw and tested up to the design stress. This test would repeat inflicting more damage until the glass finally fractured. If the empirical model is correct, the glass should crack causing the pressure to slowly leak away. A final proof test would be made on the L3 substrate(s) probably intermediate in manufacturing.

2.7.2. R&D plan for LSST filter set

Based on the initial assessment of the capabilities of commercial coating vendors, the following plan for completing the LSST filter coating procurement has been formulated.

1. Design Study
 - Define performance tradeoffs including shape
 - Coating designs, uniformity, repeatability
 - Define possible parameters to relax without compromising science
2. Risk Reduction Study
 - Engineering proof of concept.
 - Required uniformity and spectral performance developed and tested
 - Fabrication risks identified and addressed
 - Creation and analysis of witness samples
 - Develop final cost/schedule estimates
3. Production of Filters
 - Create handling tools
 - Coat filters

2.7.2.1. LSST filter coating risk reduction study

The following research and development tasks have been identified to be performed by one or more vendors in order to qualify them for a fixed price bid for the LSST filter coatings.

1. Establish procedures to distribute a uniform coating over the entire filter surface.
 - includes evaluating several coating techniques to determine best method of coating
2. Identify test procedures to measure optical performance of filters.
3. Determine optical quality of glass and coatings necessary for rejecting out-of-band transmissions.
4. Develop techniques to ensure wavelengths of pass band edges are met.
5. Establish ability to coat on two sides for spectral performance.
6. Determine exact substrate thickness to achieve desired performance goals.
 - LSST will supply substrate material to vendor
7. Monitor techniques to reduce variations.
8. Explore coating hardness
 - soft/hard coating vs. performance and cost
9. Determine spectrum shift with temperature.
10. Generate quote for coating filters.

3. CONCLUSION

We have developed a baseline design of the LSST camera optics. We have discussed optics fabrication issues with vendors and found that a substantial industrial base exists for the optics fabrication. We have also discussed the optics coating issues with vendors and found that an adequate industrial base exists for optics coating. We have developed a project execution plan, including budget and schedule for completion of the LSST camera optics. The next steps in this plan call for the completion of the tolerance analysis for the camera optics, and the completion of the RFQ for filter coating risk reduction study.

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